Thermal Radiation from Heavy Ion Collisions at RHIC

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Abstract. The direct photon spectrum measured by the PHENIX collaboration in $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV has been analyzed. It has been shown that the data can be reproduced reasonably well by assuming a deconfined state of thermalized quarks and gluons. The effects of the equation of state on the value of the initial temperature have been studied. The modifications of hadronic properties at non-zero temperature have been taken in to account.

1. Introduction

Collisions between two nuclei at ultra-relativistic energies produce charged particles - either in the hadronic or in the partonic state, depending on the collision energy. Interaction of these charged particles produce real and virtual photons. Because of their nature of interaction, the mean free path of photons is very large compared to the size of the system formed after the collision. Therefore, photons can be used as an efficient tools to understand the initial conditions of the state where it is created [1]. The purpose of the present work is to analyze this experimental data obtained by PHENIX collaboration [2] for $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV and infer the initial temperature (T_i) of the system formed after the collisions.

2. Photons from pQCD Processes

The hard collisions of initial state partons in the colliding nuclei produce photons with high transverse momentum (p_T). This contributions can be estimated by pQCD. We use the next to leading order (NLO) predictions of Ref. [3] for pp collisions and scale it up by the number of binary collisions for $Au + Au$ interactions to obtain the pQCD contributions to the direct photons.

3. Thermal Photons

We assume here that quark gluon plasma (QGP) is formed initially which then expands, cools, and reverts back to hadronic matter and finally freezes out at a temperature (T_f). Therefore, evaluation of photon spectra both from QGP and hadronic matter is required.

3.1. Thermal Photons from QGP

The photon emission rate from QGP due to Compton ($q(\bar{q})g \to q(\bar{q})\gamma$) and annihilation ($q\bar{q} \to g\gamma$) processes is evaluated in [4, 5] by using Hard Thermal Loop (HTL) approximation. Later it was shown [6] that photon production from the reactions, $gq \to gq\gamma$, $qq \to qq\gamma$, $qq\bar{q} \to q\gamma$ and $gq\bar{q} \to g\gamma$ contribute in the same order as annihilation and Compton processes. The complete calculation of photon emission rate from QGP to order α_s is completed by resuming ladder diagrams in the effective theory [7]. This result has been used in the present work.

3.2. Thermal Photons from Hadrons

For the photon production from hadronic matter all the possible reactions and decays involving π, ρ, ω, η and a_1 have been considered (see [8, 9, 10] for details). Photons from the decays of π^0, η etc are subtracted from the data and hence is not discussed here.

Various experimental [11, 12] and theoretical results [13, 14, 15, 16] suggest that the spectral functions of hadrons are modified in a hot and dense nuclear environment. There is no consensus on the nature of the vector meson modification in matter - pole shift or broadening - both experimentally and theoretically. In the present work we use Brown-Rho (BR) scaling scenario [17] for in-medium modifications of hadronic masses to indicate how far the value of initial temperature is affected when the reduction of the hadronic mass is incorporated in evaluating the photon spectra.

Transverse momentum distribution of photons produced from the fragmentation of fast quarks propagating through QGP remains almost unaffected due its energy loss [18]. Photons produced due to interactions between thermal and non-thermal partons [19] have been neglected in the current analysis.

4. Space Time Evolution

(2+1) dimensional [20] (ideal) relativistic hydrodynamics with longitudinal boost invariance [21] and cylindrical symmetry has been used for the space time evolution. We take initial thermalization time $\tau_i = 0.2$ fm/c, $T_i = 400$ MeV and the number of flavours, $N_F = 2.5$. These values reproduce the measured total multiplicity, $dN/dy \sim 1100$. The initial energy density and radial velocity profiles are taken as: $\epsilon(\tau_i, r) = \epsilon_0/[1+e^{(r-R_A)/\delta}]$ and $v(\tau_i, r) = v_0\left[1 - 1/[1 + e^{(r-R_A)/\delta}]\right]$.Here δ is the surface thickness and R_A is the radius of the colliding nuclei.

Two types of equation of state (EOS) are used to study the photon spectra: (I) Bag model EOS has been used for QGP. For the hadronic matter all the resonances with mass < 2.5 GeV $/c^2$ has been considered. (II) Results from lattice QCD [22] has also been used to show the sensitivity of the results on the EOS.

5. Results

Photon spectra is evaluated with the initial conditions mentioned above. The value of the freeze-out temperature $T_f = 120$ MeV [23] has been fixed from the p_T spectra of pions and kaons [24]. The value of the transition temperature, $T_c = 190$ MeV [25] is taken here. The resulting photon spectra is contrasted with the recent PHENIX measurements of direct photons in Fig. 1. The data is reproduced with $T_i = 400$ MeV and $\tau_i = 0.2$ fm/c. The value of T_i is smaller compared to the value obtained in Ref. [26]. Because the reduction of hadronic masses in a thermal bath increases their abundances and hence the rate of photon emission gets enhanced. Therefore, to pinpoint the actual initial temperature through photon spectra it is imperative to understand the properties of hadrons in hot and dense environment. This may be compared with the value of $T_i \sim 200$ MeV obtained from the analysis [27] of WA98 data [28] at SPS energy.

The photon spectra is also evaluated using EOS from lattice QCD. It is seen (right panel of Fig. 1) that the data can be reproduced with lower $T_i \sim 300$ MeV (and hence larger $\tau_i \sim 0.5$ fm/c). This is so because for type II EOS the space time evolution of the hadronic phase is slower than type (I). It may be mentioned at this point that the photon emission rates obtained in [7] are valid in the weak coupling limit. However, the QGP formed after $Au + Au$ collisions at RHIC energy could be strongly coupled and the photon production from strongly coupled QGP is not available from thermal QCD. Therefore, result from $\mathcal{N} = 4$ Supersymmetric Yang Mills (SYM) theory [29] has been used to estimate the photon production from QGP phase in the strong coupling limit. The rate obtained in this case could be treated as a upper limit of photon production from QGP. The results obtained in this case are compared with that from thermal QCD in right panel of Fig. 1. Photons from SYM is enhanced by about 20% as compared to thermal QCD in the p_T region ~ 2 GeV.

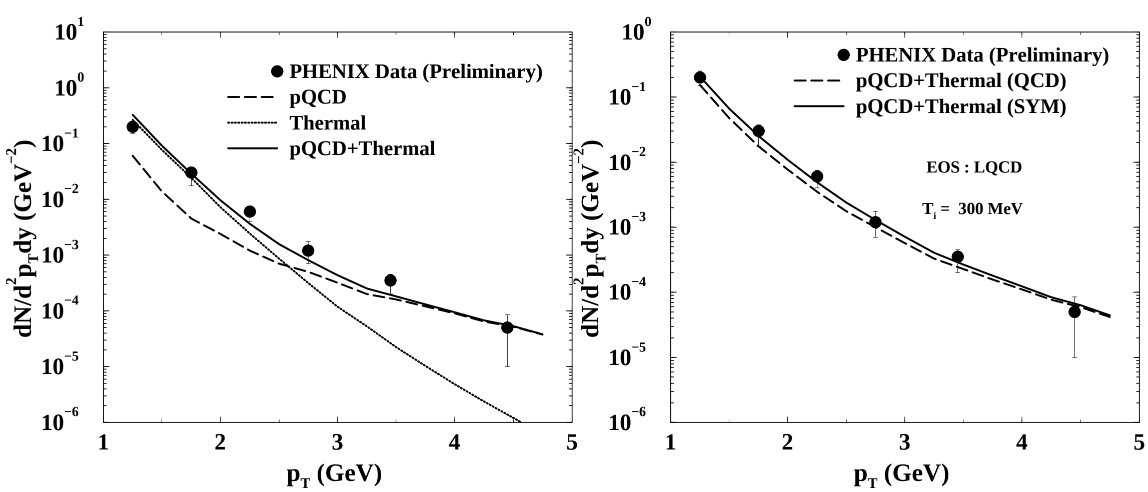

Figure 1. Left panel: Solid line depicts the total [pQCD (dashed) + thermal (dotted)] photon yield. The value of $T_i = 400$ MeV, $\tau_i = 0.2$ fm/c and EOS (I) is used here. Photon production rate from QGP is taken from [7]. Right panel: The total photon yield when EOS from lattice QCD is used. Photon production rate from QGP is taken from [7] (dashed) and from SYM [29] (solid line).

6. Summary

In summary, we have analyzed the direct photon data measured by PHENIX collaboration for $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The data can be reproduced by assuming a deconfined state of quarks and gluons with $T_i \sim 400$ MeV. However, for EOS from lattice QCD the data can be explained for lower value of $T_i \sim 300$ MeV. Photon productions from thermal QCD and $\mathcal{N} = 4$ SYM have been used for the analysis of data. In both the cases similar values of the initial temperatures are obtained.

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